Respiration Analysis of the Sternal Ballistocardiograph Signal

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Abstract

In this research a new approach for processing of Ballistocardiograph (BCG) signal is proposed in which, the respiration information is utilized to improve the averaging of the BCG signal. This method is based on our analysis that BCG cycles corresponding to the inspiration and expiration phases of respiration cycle are different in morphology. The new BCG average calculated based on this methodology is then considered as the template of the BCG signal for further processing and can be considered as the output of a clinical BCG instrument.

1. Introduction

The ballistocardiograph signal is a vital signal in the 1-20 Hz frequency range which is caused by the movements of the heart and blood, and can be recorded from the human body by noninvasive means. In the early 1930s Isaac Starr recognized that the BCG signals closely reflect the strength of myocardial contraction [1] and function of the heart as a pump. As a result of his valuable research, clinicians and medical experts for almost three decades studied the effects of different heart malfunctions by means of the BCG and proved that these malfunctions can be related to typical patterns in BCG signals [1, 2 and 6]. In addition to a number of clinical studies that have been performed with the BCG, specialized BCG instruments, including beds [3] and chairs [4], have been developed by different research groups.

However, due to the unrefined nature of the previous BCG signal acquisition technologies, the lack of interpretation algorithms, and the lack of practical devices, the current health care systems do not use BCG for clinical purposes.

The general method for processing BCG signal, followed in previous research works, has been to separate different BCG cycles corresponding to different heart beats and then to average the separated cycles. The calculated BCG average was considered as the template of the signal that features were extracted from it and based on these extracted features, the BCG signal could be classified to normal or abnormal categories [4].

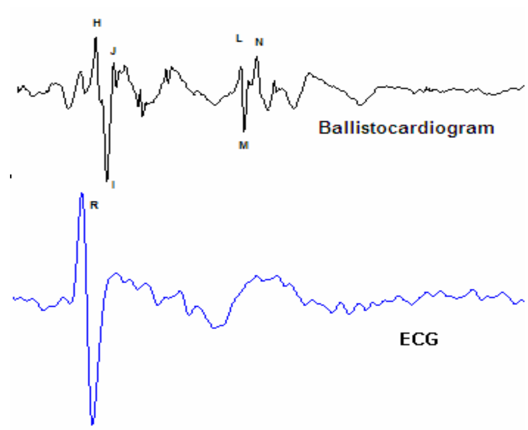

Figure 1. The accelerometer sensor was placed on the sternum while the subject was in supine position and BCG signal was recorded together with the ECG signal.

From the early investigation of BCG signal, it was clear that respiration has significant effects on the morphology of the BCG signal [1, 2]. In particular, Starr noticed that in BCG signals recorded during normal breathing, identical BCG complexes were found, not in adjacent heart beats, but in heart beats occupying a corresponding position in other respiratory cycles [1].

Considering this important respiration effect, the pre-processing approach that was taken by previous research works was simply the removal of respiration signal by high-pass filtering of respiration from the BCG signal [4, 9]. In some other research works breath holding was advised during the BCG recording to remove the respiration effect. Breath holding is uncomfortable for many patients and can not be used for ambulatory monitoring purposes. On the other hand, it is observed that holding the breath changes the morphology of the BCG signal, depending on the position in the respiratory cycle in which the breath is held [1].

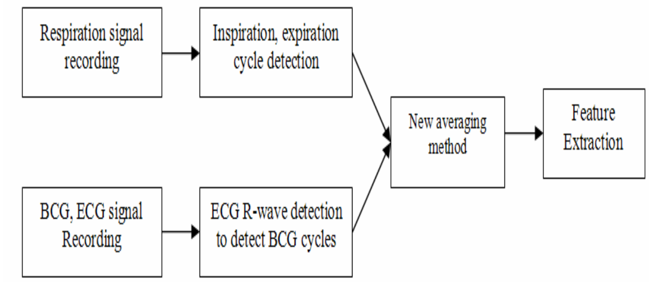

Figure 2. Our general BCG signal processing methodology using respiration information.

Our research has taken a different approach by using respiration information to improve the averaging of the BCG signal and thus, its overall processing and interpretation accuracy. This approach is based on the observation that BCG cycles corresponding to the expiration phase are more closely related to each other compared to inspiration BCG cycles and therefore, expiration cycles can statistically produce a better template for representation of the BCG cycles. Thus, based on our proposed method, just the expiration cycles are selected to be averaged and presented as the output of BCG instrument.

The above finding is also fortified by the early clinical studies conducted by Starr [1] and Brown [2] stating that in many cardiac abnormalities the expiration cycles get affected first. By the progress of the abnormality the inspiration cycles start getting affected too. Thus, in order to have an earlier diagnosis of the cardiac abnormality it is better to concentrate on the expiration cycles. This does not deny the fact that the inspiration cycles can also be used to extract information about the cardiac cycle but it suggests that if there is going to be one averaged beat presented to the users of BCG instrument as the output of the system, this average is better to be done over the expiration cycles.

The novelty of the current research is that in our proposed method rather than simply removing the respiration effect from the signal, as was done previously by others, we instead utilize the respiration information to improve the averaging of the BCG signal. This in turn opens a new improved processing and interpretation methodology, contributing to a possible adoption of BCG, and also other mechanical signals originating from the heart, for ambulatory and clinical usage.

2. Methodology and test setup

The BCG dataset was acquired from subjects with and without heart-related pathologies, most of whom were provided by Burnaby General Hospital. Out of the 45 subjects taking part in our study, 19 were females and 26 were males. The subjects were between 44 to 80 years old, with the average age of 66 years. The ethical approval for this data acquisition was granted by Simon Fraser University and the Fraser Health Authority of British Columbia, Canada.

The data acquisition involved measurement of BCG, twelve lead ECG, pulse oximetry, respiration and heart sounds. All of the signals were acquired by a Biopac biological data acquisition system [11]. All subjects were tested before and after exercising on a treadmill. A sample of the data can be seen in Figure 3. The BCG signal was measured using a high sensitivity (1000 milivolts/g) accelerometer which was positioned on the sternum. The accelerometer sensor was factory calibrated, weighed 54grams, and was connected to a charge amplifier [10]. The ECG signal was measured in twelve leads and the R-wave of the second lead of the ECG signal was used to identify BCG cycles.

The respiration was recorded using a strain gauge transducer that measures the changes in thoracic circumference, using a belt which is fastened to the subject's thorax. The subjects were asked to keep the normal pattern of respiration and to pause and hold their breath on maximum inhalation and maximum exhalation respectively for short periods of time not exceeding four seconds. By keeping these periods short and giving proper instructions to the subjects we tried not to stop the normal pace of breathing but the purpose behind the pause and hold process was to clearly differentiate the BCG cycles corresponding to inspiration from the expiration ones and to increase the accuracy of the statistical analysis explained in the section five of this paper.

The general methodology which was followed in this research is outlined in Figure 2. Averaging a number of BCG beats provides a more statistically reliable template for processing and interpretation. We use the averaging for BCG signal similar to other physiological data, to remove noise from the signal and reduce the effect of possible transient changes in the signal.

To prove the usability of our proposed averaging method, which will be explained in details in the next section of the paper, we have calculated the averages during the inspiration phase and expiration phase separately. In order to implement this averaging the following steps were followed:

a) The points corresponding to the start of inspiration and expiration cycles were found from the respiration signal.
b) The R wave peaks of the ECG signal, as the timing mark of individual BCG beats, were detected.
c) Those R-R intervals that were shorter than three quarter of averaged R-R interval length were removed to avoid very short beats and the

shortest remaining beat was considered as the standard beat.

d) The remaining beats were truncated to match the standard beat's length.

e) A linear regression line was fitted to each cycle and the signal was subtracted from this line in order to remove the slight drift caused by respiration on the level of the BCG signal.

f) The BCG beats corresponding to inspiration were averaged sample-by-sample to create the inspiration BCG average and by the same procedure the BCG beats corresponding to expiration were averaged to create the expiration BCG template.

An approach based on piecewise linear approximation has been developed to remove the changes of the signal level which is created by respiration. This method is based on approximating the respiratory component of the signal by line segments of equal length and the residual signal, obtained after subtracting the piecewise linear approximation from the actual signal will not be affected by changes in the level of the signal because of the chest movement. The piecewise approximation is done by fitting a line to each BCG cycle using a least square method [3].

3. Results

As a measure of similarity for all the subjects, all the inspiration cycles were cross correlated, and the average of all their correlation coefficients, compared to one another, was considered as the measure of similarity of the inspiration cycles for that individual subject. The same procedure was repeated for expiration cycles and for all the forty five subjects.

As an example, in subject four, and for his post exercise signal, fifteen inspiration cycles were selected and 15 multiplied by 14, or 210, correlation coefficients of cycles compared to each other were calculated and averaged, to compute the similarity index of 0.6558 for the inspiration cycles. The same procedure for subject four's expiration cycles resulted in the similarity index of 0.9409.

At the end, it was noticed that expiration cycles were 0.1272 more in the average similarity index, over all the subjects, compared to inspiration cycles for pre exercise signal. In order to have a statistical analysis of the importance of this difference, a t-test was used to find out whether mean difference in a response variable, consisting the difference between expiration and inspiration values, was equal to zero for the pre exercise signal. The analysis showed a significant statistical difference (p-value<0.01) between the inspiration and expiration averages. The same analysis was performed for the post exercise signal and again a p-value less than 0.01 was obtained. These results suggest a meaningful difference between the inspiration and expiration cycles and that the expiration cycles are statistically more closely related to each other compared to inspiration cycles. This can be attributed to the fact that expiration is a passive process in which muscles relax and the thorax moves more smoothly, while inspiration is an active process in which the muscles contract and add more movement artifacts to the BCG sensor which is placed on the sternum.

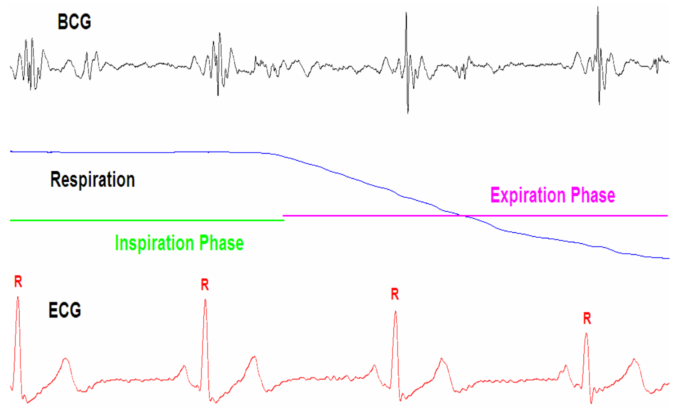

Figure 3. The signal at the top of the figure is the BCG signal of a patient who had myocardial infarction three years ago (subject 35). The signal in the middle is part of one respiration cycle in which the inspiration and expiration phases are separately shown. The difference of BCG signals corresponding to inspiration and expiration cycles can be observed from the morphology of the BCG waves.

This statistical difference further proves that averaging the expiration cycles and excluding the inspiration cycles can result in a better statistical representation of BCG signal which can be used in further processing of the signal, such as feature extraction, for diagnostic purposes.

4. Conclusion and future work

Based on our study and conducting the BCG survey for two years we observe that the BCG signal is a non-stationary signal and averaging a number of BCG beats provides a more statistically reliable template for analysis and interpretation. The focus of this research work was the introduction of a novel averaging method to the general methodology used previously to process the BCG signal. The novelty of the proposed method is that, rather than removing the respiration effect from the BCG signal, we utilize the respiration information to improve the averaging and interpretation of BCG signal in diagnosis of cardiac malfunctions.

The statistical analysis provided that expiration cycles are better candidates for calculation of this BCG average.

Improvement of the averaging algorithm, explained in this paper, results in extraction of features which better represent the BCG signal and can improve the classification accuracy of normal and abnormal BCG patterns.

In parallel to this research, other parts of the methodology diagram of Figure 2 are under investigation in our lab, CIBER, and new sensors are being developed that combine ECG and BCG sensors in a small polymer package that can send the data wirelessly to a computer [5]. This new sensor will significantly facilitate the signal acquisition procedure in our future clinical tests. On the other hand, a novel method of detecting mechanical movement of the heart, with absolutely no connection to the subject's body, which is based on the radar technology, is under investigation [6].

Apart from the hardware developments, we have new approaches in terms of algorithms for processing of the BCG signal [7] and the part of our research, which is detailed in this paper, is related to our new approaches in processing of the BCG signal considering the information embedded in the synchronous respiration signal.

We anticipate that further development of our research on the BCG signal will finally provide us with an additional diagnostic methodology and clinical instrument for gathering information about the heart's dynamics and abnormalities.

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